BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B69 07061

SUBJECT: Updated S-II Longitudinal Structural Model - Case 320

DATE: July 18, 1969

FROM: H. E. Stephens

ABSTRACT

The S-II 27 longitudinal structural model described in Memorandum for File, "S-II 27 Degree-of-Freedom Longitudinal Structural Model - Case 320, dated May 23, 1969, by H. E. Stephens, has been revised to include an additional node in each the thrust structure and LOX tank bottom.

The model now duplicates the AS-504 inboard engine/ LOX sump phase relationship as observed in flight, and give a reasonable correlation of calculated amplitudes and frequencies to flight response.

(NASA-CR-107164) UPDATED S-2 LONGITUDINAL STRUCTURAL MODEL (Bellcomm, Inc.) 13 p

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MEMORANDUM FOR FILE

1. An S-II longitudinal structural model was described in Reference 1, but the modal data from that model did not duplicate the engine-LOX sump phase relationship as observed on the AS-504 flight. This memorandum describes the revision of that model to include an additional thrust structure node and LOX tank node, and the correlation of the model results with observed flight data.

2. The thrust structure stiffness matrix of Reference 2 was used as the basis for adding another node in the thrust cone, node 28 Figure 1. In the absence of detail information, the stiffness values of Reference 2 were reduced by 5 percent as an allowance for the AS-504 thrust structure being lighter than for AS-503. A value for the center engine beam stiffness, K24 Figure 1, was selected to give a beam frequency of 16.8 cps as observed in flight. This revision also shifted the higher frequency thrust structure mode from 21.7 to 23 cps with a decrease in inboard engine gain, while increasing the gain of the 15+ cps thrust structure mode.

3. The single degree-of-freedom LOX tank bottom was changed to a two mass system as shown in Figure 2. Distribution of the LOX mass between the two nodes, and a choice of values for the equivalent tank bottom spring constants was determined at each time point in a manner to duplicate the first two observed LOX tank frequencies. The values of the frequencies for these two modes, based on S-II static firings and the MINI-A test, are plotted in Figure 5 and listed in Table I.

Referring to Figure 2, let:

$$A = (K_1/M_1)\big/(K_2/M_2)$$

$$B = M_2/M_1, \text{ and}$$

$$R = \omega_2/\omega_1$$

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The equation for the frequencies of the two mass system, as given in Figure 2, then becomes:

$$\omega^2 = \left((1+A+B) \pm \sqrt{(1+A+B)^2 - 4A} \right) K_2/2M_2 .$$

The smallest value of R to be used in this modeling exercise, as determined by the test data, is 1.43, for which it is found that B must be less than 0.125 for the two frequencies to exist. For R = 1.43 and B = 0.125, A is found to be 1.03. For a limiting case of ω_2 near ω_1, it is found that the maximum allowable value of A+B approaches 1, compared to A+B = 1.155, as computed above. The limiting case of A+B = 1 is used for this problem and is found to have little effect on the value of B. For larger values of R, say 3, values of A and B should be computed on an individual basis for each time point. The following equations result:

$$A = 1 - \frac{(R^2-1)^2}{(R^2+1)^2}$$

$$B = 1 - A$$

$$M_1 = \frac{M_{TOTAL}}{(1 + B)}$$

$$M_2 = M_{TOTAL} - M_1$$

$$K_2 = \omega_2^2 M_2/(1 + \sqrt{B})$$

$$K_1 = AK_2/B$$

A weak spring of 10,000 pounds/inch was added between the LOX sump and inboard engine to represent the effect of the LOX suction line. It was found that this spring only affected LOX tank response near burnout as the LOX was depleted (T=360 to 370 seconds). In earlier flight times, the effect of this spring must be included when examining the center beam response frequency.

The time variant LH_2 and LOX tank input parameters are given in Table I, with the computed spring constants and mass distribution tabulated in Table II.

4. The first nine S-II longitudinal modal frequencies versus flight time are plotted in Figure 3, with modes 4 through 9 also shown in Figures 4 and 5 on an expanded scale for T = 200 to 370 seconds. Phase relationships are shown in Figure 4, and the major component frequencies of interest are plotted in Figure 5.

5. Salient features of the observed flight data were:

   a. A maximum inboard engine acceleration of 12 g's, zero to peak, at about T = 342 seconds and 16.8 cps. Based on Pc = Psi 0-peak.

   b. A LOX tank sump acceleration of 8 g's at the time of maximum inboard engine acceleration, which was in phase with the inboard engine.

   c. An inboard engine acceleration response frequency increase from 16.8 cps at T = 342 seconds to 19 cps at burnout, with the measured phase angles indicating that the vehicle response frequency during this period corresponded to that of a structural mode. During this period the inboard and outboard engines were out of phase and the LOX sump in phase with the inboard engine. Just prior to T = 342 seconds, the inboard and outboard engines were in phase.

6. Correlation of the computed data with flight data is as follows:

   a. From Figure 4, it is seen that for the 5th mode the engines go out of phase at 17 cps and T = 340 seconds, as compared to 16.8 cps and T = 342 seconds in flight. The 5th mode LOX sump response is in phase with the inboard engine during this period, as observed in flight.

b. The flight observed phase angles indicate, that just prior to T = 340 seconds the total vehicle system is being forced at 17+ cps and responding to a structural mode whose natural frequency is slightly less. Qualitatively, the existence of the 5th mode at 17 cps and T = 340 seconds would permit this behavior when considering the 17.3 cps system flight response at T = 340 seconds, as shown in Figure 5. The flight response frequencies, as taken from the spectrum analysis, are plotted on Figure 5 and follow the same general shapes as the computed modal frequencies. More specifically:

(1) The plot of lowest frequency LOX sump response shown on Figure 5 coincides with the 4th vehicle mode until T = 260 seconds, the 4th mode being the total vehicle* structural response to the first LOX tank mode. Between T = 260 and T = 340 seconds, the vehicle system response makes a transition (in frequency) from the 4th to 5th structural modes and then follows the 5th mode to about T = 360 seconds. In this same system response transition period, T = 260 to 340 seconds, the vehicle structural mode governed by the 1st LOX tank mode also makes a transition from the 4th to 5th structural modes, with the 4th mode becoming the first thrust structure mode.

(2) The 17 to 19.7 cps flight response between T = 240 and 310 seconds, Figure 5, follows the calculated total vehicle structural response to the 2nd LOX tank mode.

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*As used here, system response referes to total stability loop, whereas vehicle structural response refers to total vehicle structural modes only.

c. Amplitudes of the calculated 5th mode during the time of maximum response are compared with flight data in Table III.

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H. E. Stephens

Attachments
Figures 1-5
Tables I, II, III
References

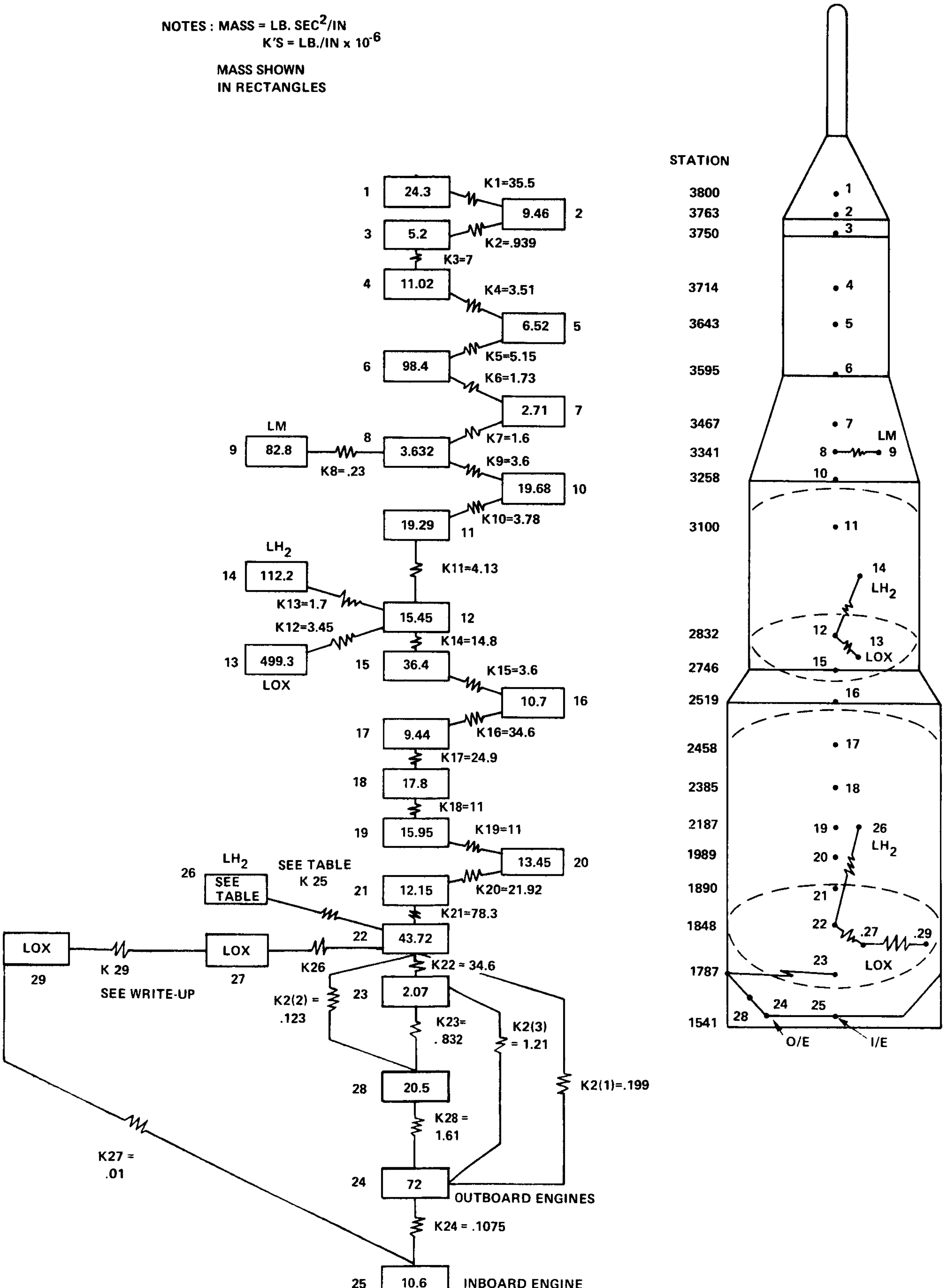
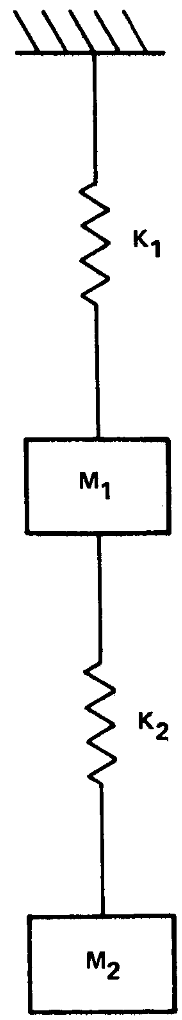


FIGURE 1 - AS 504 CONFIGURATION II LONGITUDINAL MODEL, 29 DOF.



$$\omega^2 = \frac{D \pm \sqrt{D^2 - 4E}}{2}$$

$$D = \frac{K_1 + K_2}{M_1} + \frac{K_2}{M_2}$$

$$E = \frac{K_1 K_2}{M_1 M_2}$$

FIGURE 2 - TWO MASS LOX TANK MODEL

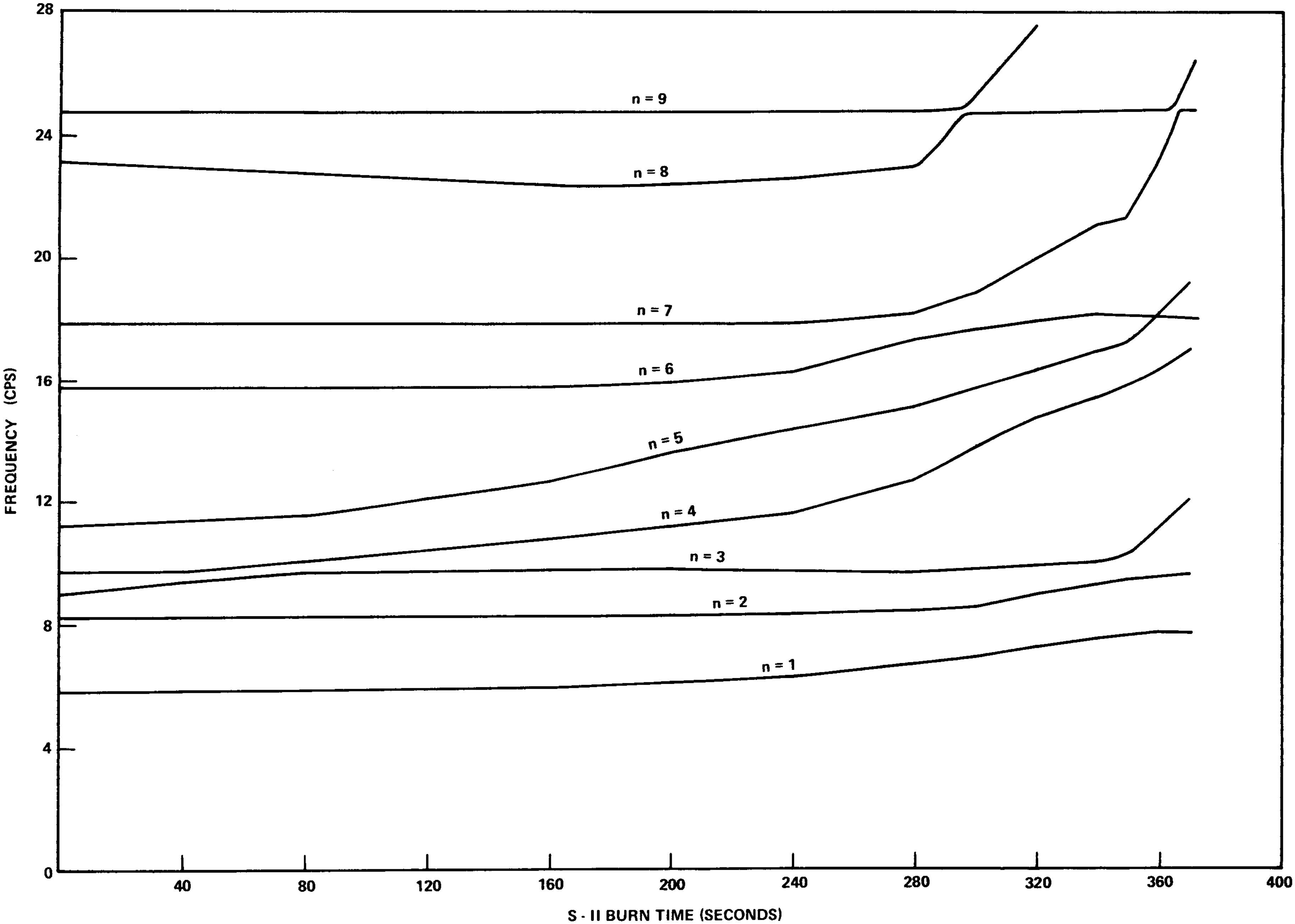


FIGURE 3 - AS 504 - S II LONGITUDINAL STRUCTURAL MODES
BELLCOMM 29 DOF MODEL

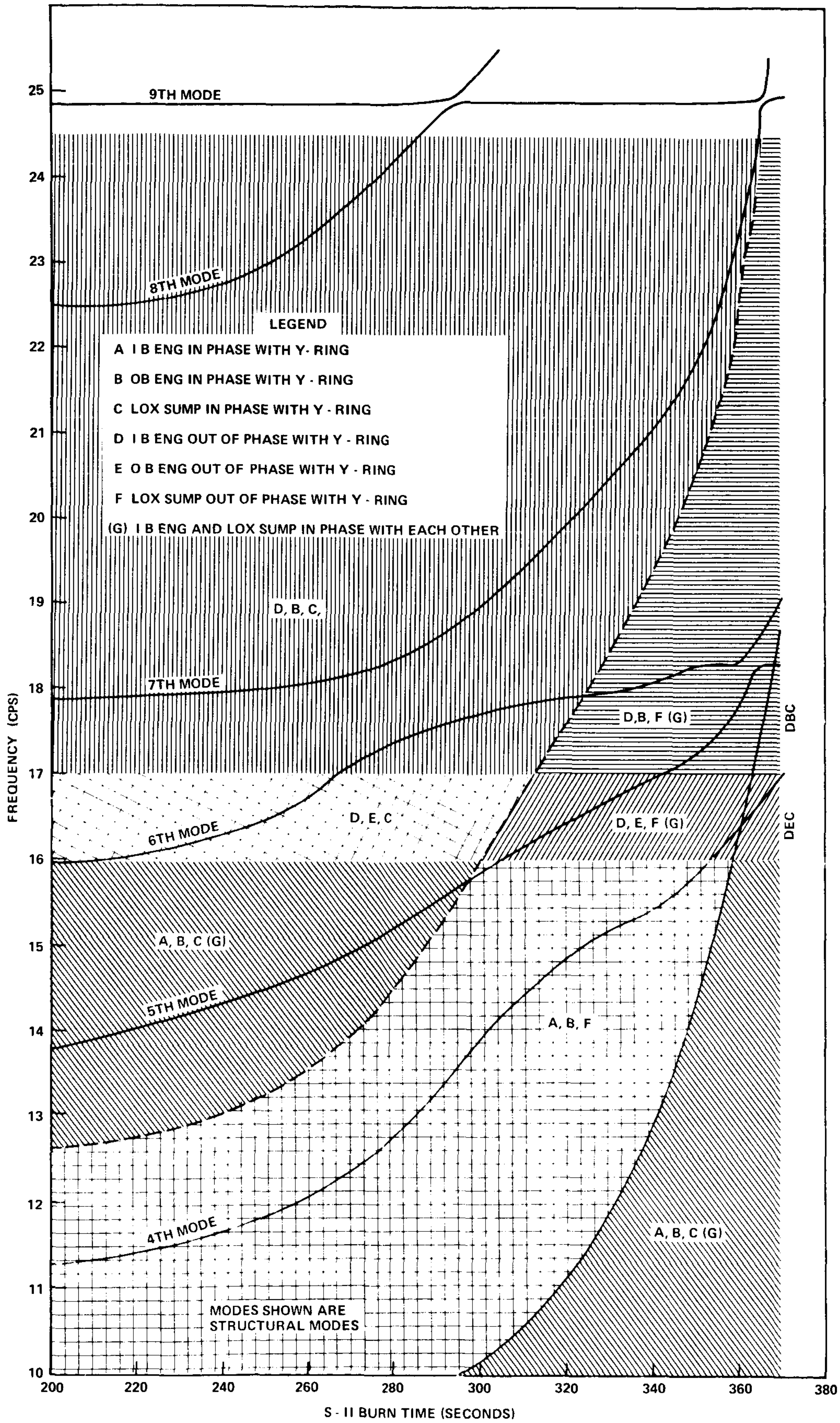


FIGURE 4 - ENGINE - LOX SUMP PHASE RELATIONSHIP, LONGITUDINAL MODES
AS - 504 S II BURN
T = 200 TO 370 SECONDS

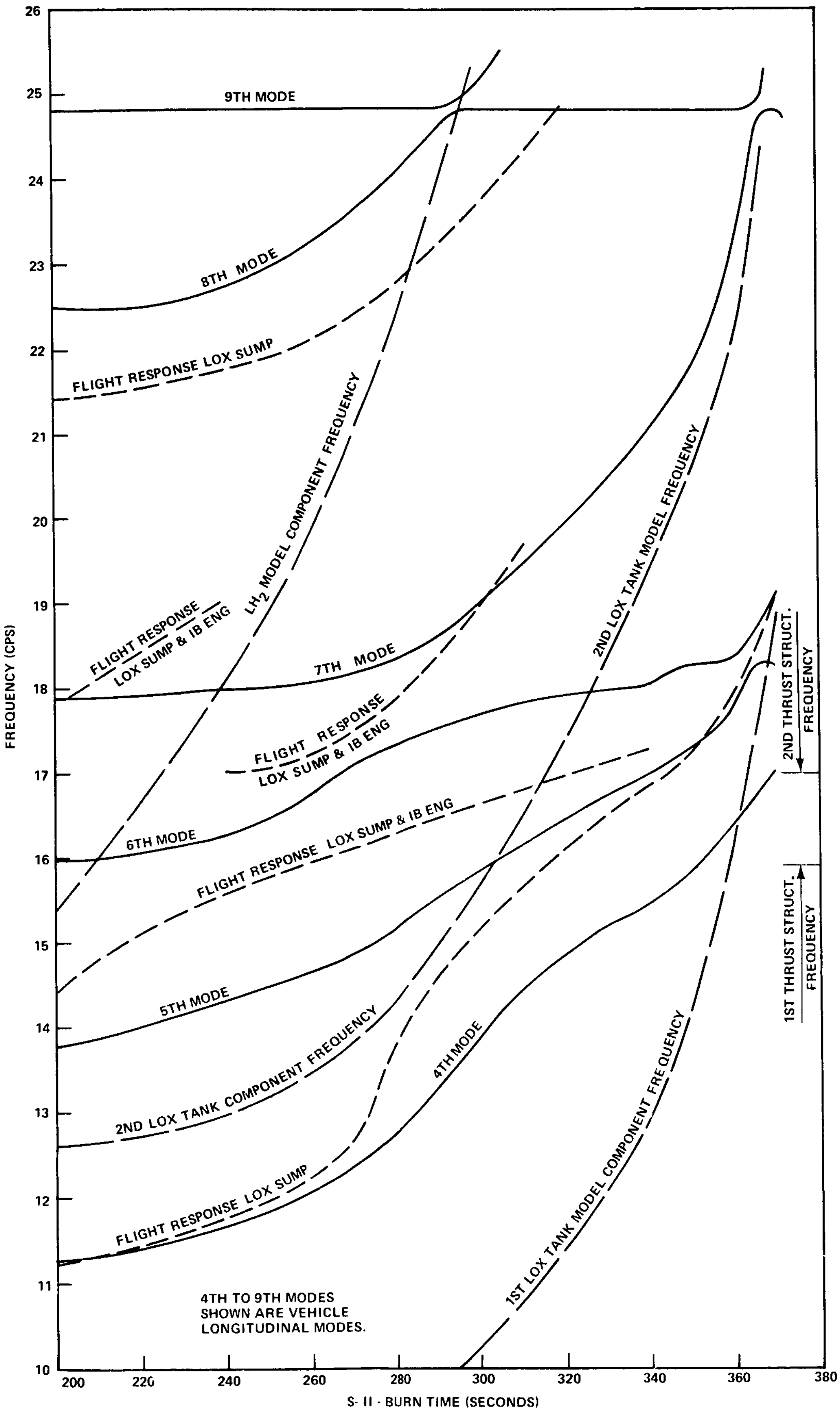


FIGURE 5 - AS 504 - S II PARTIAL LONGITUDINAL VEHICLE & COMPONENT FREQUENCIES.

TABLE I

AS-504 INPUT DATA

TIME VARIANT PROPELLANT

WEIGHTS, SPRING CONSTANTS & FREQUENCIES

	(LBS) LH_2 Wt x 10^{-4} (Includes 2100 lb struct)	(LBS) LOX Wt x 10^{-4} (Includes 2600 lb struct)	K25 LH_2 #/in x 10^{-6}	LOX TANK BOTTOM *ω_2 (cps)	ω_1 (cps)
0	15.774	81.947	1.4	12	8
40	14.1	72.885	1.47	12	8
80	12.41	63.588	1.55	12	8
120	10.921	54.549	1.65	12	8
160	9.21	45.242	1.75	12.2	8
200	7.505	35.924	1.8	12.6	8
240	5.749	26.595	1.9	13	8
280	4.084	17.296	2.0	14.4	9
300	3.261	13.278	2.1	16	10.2
320	2.448	9.454	2.15	17.8	11.6
340	1.634	5.661	2.2	19.4	12.8
345	1.431	4.662	2.25	19.8	13.3
350	1.228	3.717	2.3	20.5	14
360	.8237	2.239	2.35	21.9	15.1
370	.535	.542	2.4	23.3	16.3

* Tank bottom component frequency without effect of spring between tank bottom and center engine.

TABLE II

CALCULATED LOX TANK BOTTOM

SPRING CONSTANTS AND MASS DISTRIBUTION

(SEE FIGURE 2 FOR IDENTIFICATION OF K's AND M's)

S-II BURN TIME SECONDS	K_1 $(x10^{-6})$	K_2 $(x10^{-6})$	M_1 $\frac{\#\text{-sec}^2}{\text{in}}$	M_2 $\frac{\#\text{-sec}^2}{\text{in}}$	$\frac{K_1}{K_2}$	$\frac{M_1}{M_2}$
0	6.47	1.12	1849.	273.	5.75	6.75
40	5.75	.999	1645.	243.	5.75	6.75
80	5.02	.871	1435.	212.	5.77	6.75
120	4.30	.747	1231.	182.	5.76	6.76
160	3.55	.682	1009.	163.	5.22	6.68
200	2.86	.622	789.	141.	4.6	5.59
240	2.09	.539	572.	117.	3.88	4.88
280	1.75	.404	377.	70.8	4.22	5.32
300	1.72	.364	293.	51.1	4.7	5.75
320	1.58	.303	211.	40.	5.21	5.3
340	1.15	.207	127.	19.4	5.56	6.55
345	1.01	.170	106.	15.2	5.9	5.97
350	.891	.139	84.8	11.4	6.4	7.45
360	.628	.091	51.5	6.5	6.9	7.9
370	.177	.024	12.6	1.48	7.4	8.4

TABLE III

LOX TANK MODE CHARACTERISTICS

TIME (S-II BURN) SECONDS	FREQUENCY		INBOARD ENG RESPONSE / OUTBOARD ENG RESPONSE		INBOARD ENG RESPONSE / LOX SUMP RESPONSE		CRITICAL % DAMPING REQ'D TO MATCH CALCULATED TO FLIGHT INBOARD ENGINE RESPONSE
	FLIGHT	CALCULATED	FLIGHT	CALCULATED	FLIGHT	CALCULATED	
340	16.8	16.95	15.0	11.6	1.5	1.69	*2.9
345	17.0	17.05	13.0	9.3	1.5	1.46	*2.8
350	17.2	17.2	11.0	7.0	1.3	1.17	*2.4
**360	17.9	(5th) 17.4	5.5	4.2	1.1	.63	
		(6th) 18.5		2.5		.58	
370	19.1	18.7		.59		.07	

* In a June 10, 1969, presentation to the POGO Working Group at MSFC, The Martin Co. stated that an analysis of AS-504 Flight Data indicated 2 to 3% damping in this mode and time frame.

** T = 360 seconds is in the transition period when tank mode is shifting from 5th to 6th mode. Hence no clearly defined tank mode at T = 360 seconds.

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REFERENCES

1. "S-II 27 Degree-of-Freedom Longitudinal Structural Model", Case 320, Memorandum for File, May 23, 1969, H. E. Stephens.

2. "SA-503 'Manned' Longitudinal Structural Dynamic Characteristics", Boeing, Huntsville, July 17, 1968, 5-9570-JH-395.